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高温升蒸发型燃烧室的设计

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摘　要: 为了满足某地面实验设备对燃烧室高温升的要求, 设计了温升为 1 350 K的蒸发型燃烧室。根据燃烧室总体结构, 设计了燃烧室的主要部件。通过对燃烧室的气动热力计算, 确定出了燃烧室总体和火焰筒开孔的尺寸, 并对燃烧室进行了一定的性能实验。实验及应用结果表明, 所设计的燃烧室具有工作安全可靠、结构简单、空间利用率高、升温速度快及排气清洁的特点。在整个工作范围内, 燃烧效率达到 0.95～0.97, 出口温度场不均匀度低于 0.09, 符合设计要求。

关　键　词: 燃气轮机; 高温升; 蒸发型; 燃烧室

中图分类号: TK16; TK473.2　　文献标识码: A

引　言

半个多世纪以来, 随着燃气轮机的发展, 燃烧室技术也相应得到了很大的提高, 例如其结构由最初的单管发展到环管, 进而到环形及短环形。目前, 航空燃气轮机为了大幅度提高推重比及功重比, 其燃烧室是朝着高温升方向发展, 而低污染排放则是民用燃气轮机燃烧室今后主要的发展方向, 这两方面的发展趋势给燃烧室的研究和发展带来了很大的技术挑战[1～3]。因此, 一些工业发达的国家, 针对发展高性能燃烧室的关键技术, 都制订了各自的研发计划, 例如美国正在实施的多用途经济可承受的先进燃气涡轮发动机计划 (VAATE)和超级高效发动机计划 (UEET)等。

燃烧室不仅是燃气轮机的核心部件之一, 而且也是某些地面实验设备的关键部件。例如以燃烧室作为加热器的高温热风洞, 由于其工质性质与燃气轮机的相近, 因而可以利用其开展涡轮部件的性能试验, 测温传感器的校准与标定, 高温复合材料的应用环境性能模拟等多种与燃气轮机相关的科研实践活动。本研究根据某热风洞的气源条件及对燃烧室的性能要求, 设计了一种以航空煤油为燃料的高温升蒸发型燃烧室, 其最大温升为 1 350 K。燃烧室的主要设计参数如表 1所示。

表 1　燃烧室的主要设计参数

	数　值
空气流量 /kg·s^{-1}	0.30
进口压力 /MPa	0.13
进口总温 /K	523
出口总温 /K	1873
燃烧效率	0.96
温度系数	≤0.10
总压恢复系数	0.93

1　燃烧室结构设计

对于使用液态燃料的燃烧室, 按供油方式通常可主要分为压力雾化型、空气雾化型和蒸发管型。由于蒸发管型具有结构简单、火焰筒长度短、供油压力低、燃烧效率高、排气清洁以及出口温度场容易控制等诸多优点[4～5], 因此在设计中采用了蒸发管环形燃烧室的结构方案。所设计的燃烧室主要由进口扩张段、壳体、火焰筒、中心蒸发管、燃油预热器、喷嘴、陶瓷收敛段和点火器等部件组成, 轴向长度 595 mm, 壳体直径 272 mm, 进口直径 150 mm, 出口直径 80 mm, 其总体结构如图 1所示。

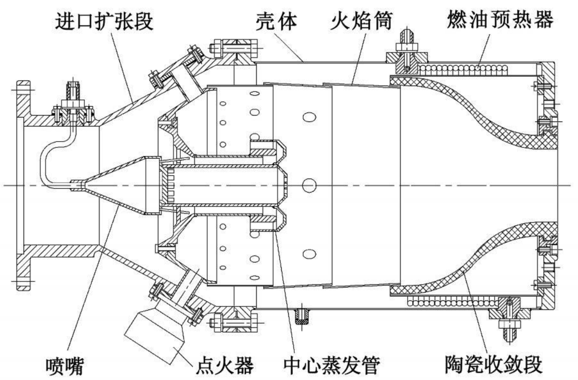

图 1　燃烧室总体结构

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1.1　进口扩张段和壳体

进口扩张段采用直线壁面造型规律，保证气流在扩张通道中尽可能地稳定减速流动，不产生分离。除扩压减速外，进口扩张段还为火焰筒、喷嘴及点火器的安装和固定提供支撑和定位。燃烧室壳体为整体筒状结构，在壳体后段的下方和上方分别设有进油嘴和出油嘴，在壳体前段的下方设有漏油塞，用来排放燃烧室内的积油。

1.2　火焰筒和中心蒸发管

火焰筒由分流锥及火焰筒筒体组成。位于火焰筒前端的分流锥将进入燃烧室的空气分成一次空气和二次空气，一次空气进入中心蒸发管内，二次空气则进入二股腔道内。火焰筒前段依靠进口扩张段上的3个定位销进行固定，其后段则插入陶瓷收敛段内，从而实现火焰筒的轴向、径向和周向定位，同时允许火焰筒工作时产生一定的热膨胀。中心蒸发管由内筒、外筒、反向导流环及后端盖组焊而成，如图2所示。蒸发管内筒引入了少量空气，作为二次空气从蒸发管后端进入燃烧区，实践表明这种设计可有效加强富油时火焰筒中心处的燃烧强度，提高富油燃烧效率，缩短火焰，使燃烧室出口温度场更均匀。

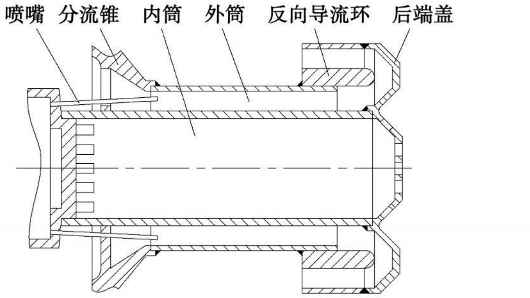

图2　蒸发管结构示意图

1.3　燃油预热器和喷嘴

在高温升燃烧室中，利用燃气热量预热燃油是改善燃烧过程的有效手段，因此在燃烧室中设置了燃油预热器，预热后的油温可达80～100 ℃。燃油预热器为体内螺旋式结构，铜制预热管安置在壳体后段与隔热屏之间的环腔内，隔热屏的作用是对预热管给予保护。预热后的燃油从壳体上方的出油嘴输出，通过油管引入进口扩张段上的进油嘴。燃油喷嘴采用6个内径为0.6 mm的直射式喷嘴，喷嘴座嵌入在蒸发管的内筒中，保证6个喷嘴中心对称地分布在蒸发管内外筒之间的环腔内。

1.4　陶瓷收敛段和点火器

陶瓷收敛段是燃烧室内温度最高的部件，红外探测结果显示，其出口内壁温度可达1 200～1 400 ℃，这是高温陶瓷材料所能允许的。在装配结构上，陶瓷收敛段采用了套齿浮动安装方式，其在燃烧室中只受到径向和轴向限位，但均留有热膨胀间隙。燃烧室采用一套WP-5发动机的预燃式点火器，具有点火可靠、点火能量大的特点，为了简化结构，将火焰筒的一个定位销与点火器的传焰管设计为一体。

1.5　燃烧室的安全及冷却

由于燃烧室的温升高，因此其金属部件的冷却是设计中必须考虑的问题。蒸发管工作时处于高温燃气中，其依靠内部燃油的附着、吸热与蒸发可得到充分冷却，示温漆显示蒸发管壁面温度不超过900 ℃，由于蒸发管是采用长期工作温度为950～1 050 ℃的耐热钢锻件制造，因而不会带来安全问题。火焰筒筒体虽然是采用耐热钢板材经冲压焊接而成，而且其外部也有二次空气流过，但由于其内壁燃气温度很高，因此在火焰筒上共设置了四道冷却气膜，均为波纹环式结构。

2　燃烧室的气动热力计算

在燃烧室的结构确定后，应当进行燃烧室的气动热力计算。计算的主要目的是确定燃烧室的空气流量分配、火焰筒内的沿程气动热力参数、余气系数、容热强度和流阻损失等是否合理，以此作为调整燃烧室主要尺寸和火焰筒开孔尺寸的依据。根据火焰筒的进气情况，选取9个计算截面，从1-1～9-9截面依次为蒸发管反向导流环出口、头部气膜孔、头部孔、主燃孔、第二道气膜孔、蒸发管内筒出气孔、掺混孔、第三道气膜孔及尾部气膜孔，计算模型如图3所示。

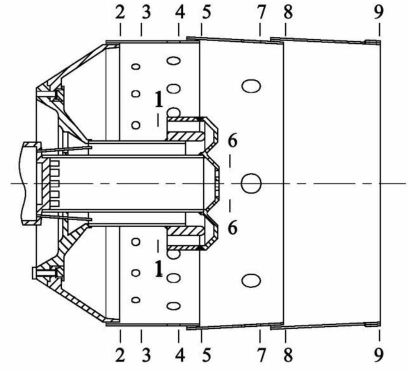

图3　计算模型

利用一套适用于工程设计的自编程序, 采用流阻法和一元流法对燃烧室进行气动热力计算。首先用流阻法初步确定流过火焰筒各排孔的流量, 以其结果作为一元流法计算的初值, 然后利用一元流法依次计算各截面的相关参数, 并对最后计算出的叠加流量进行校核。如果所计算的各排孔流量的总和与燃烧室进口流量之差达不到精度要求, 则应对火焰筒头部各排孔的流量进行调整, 根据重新分配后的流量关系, 重复上述计算直到满足精度要求为止, 计算结果如表 2所示。从表可见, 各截面的余气系数、各排射流孔的流量百分数及火焰筒内各截面的温度分布和压力损失等均处于合理范围内。

表 2　空气流量分配及流程参数的计算结果

截面序号	余气系数	各排孔流量 / $kg \cdot s^{-1}$	各排孔叠加流量 / $kg \cdot s^{-1}$	各截面流速 / $m \cdot s^{-1}$	各截面总温 / K	各截面总压 / MPa
1	0.35	0.060	0.060	6.54	1 519.56	0.128
2	0.41	0.009	0.069	7.34	1 519.56	0.128
3	0.62	0.033	0.102	10.45	1 519.56	0.127
4	1.12	0.090	0.192	29.20	2 385.13	0.127
5	1.18	0.010	0.202	29.82	2 323.39	0.126
6	1.26	0.013	0.215	30.57	2 249.47	0.126
7	1.57	0.062	0.277	33.79	1 957.50	0.125
8	1.62	0.011	0.288	34.29	1 915.72	0.125
9	1.66	0.012	0.300	34.82	1 873.13	0.125

3　燃烧室性能实验

3.1　实验装置与测量方法

根据热风洞对燃烧室的性能要求, 以一台罗茨风机作为气源, 在燃烧室进口压力为 0.12 MPa空气流量为 0.33 kg/s进口温度为 523 K出口温度为 1 473 ~1 923 K的条件下, 对燃烧室进行了燃烧效率特性和出口温度场均匀度实验。实验中空气流量采用流孔板测量, 燃烧室进口温度采用镍铬 —镍硅热电偶测量, 出口温度采用双铂铑热电偶测量, 进口压力采用总压探针测量, 燃油流量采用齿轮流量计测量。实验中采取四点周向均布并按等环面规律测量燃烧室的出口温度场, 每支温度耙设 3个测点, 实验状态如图 4所示。

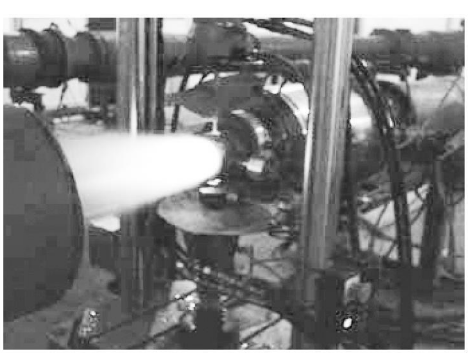

图 4　燃烧室的实验状态

根据能量平衡原理, 燃烧室的燃烧效率 η_c可通过焓升法来确定[6], 即

$$\eta_c = [\alpha L_0 (i^*_{3a} - i^*_{2a}) + H^*_3 - H_0] / H_u \quad (1)$$

式中: α—燃烧室的余气系数; L_0—燃油的理论空气量; i^*_{3a}、i^*_{2a}—空气在燃烧室出口和进口温度时的单位热焓; H^*_3—燃烧室出口温度的等温燃烧焓差; H_0—基准温度 (288 K)的等温燃烧焓差; H_u—燃油的热值 (43 200 kJ/kg)。

衡量燃烧室出口温度场均匀度的温度系数 δ_m可计算为:

$$\delta_m = \frac{T^*_{3max} - T^*_{3m}}{T^*_{3m} - T^*_2} \quad (2)$$

式中: T^*_{3max}—燃烧室出口截面的最大温度; T^*_{3m}—燃烧室出口截面的平均温度; T^*_2—燃烧室的进口温度。

3.2　实验结果和分析

实验结果分别如图 5和图 6所示。蒸发型燃烧室属于油气预混的供油方式, 由于燃烧室工作时蒸发管处于火焰区, 通过金属管壁会吸收大量的热, 因此从蒸发管喷出的基本上是气态的富油混合气。当这部分富油混气与进入火焰筒头部的二次空气混合后, 形成接近于燃烧恰当比的最适合于燃烧的均匀混气, 加之设计中采取了燃油预热的措施, 增强了蒸发管的预热预混效果, 因而燃烧室的燃烧效率高, 排气清洁, 温升大并且升温速度快。

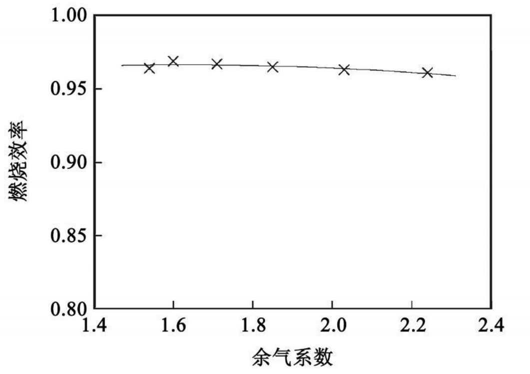

图 5 燃烧效率特性

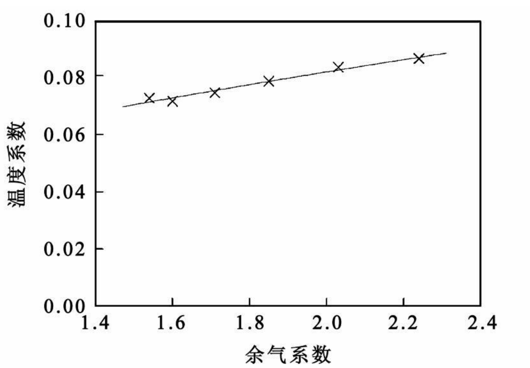

图 6 温度场均匀度

由图 5可以看出, 在实验状态范围内, 燃烧效率变化不大且都在 0. 95 ~0. 97之间, 这完全符合蒸发管环形燃烧室的工作特点, 即在一定的余气系数范围内, 燃烧效率较高, 且随余气系数的变化不敏感。由于蒸发型燃烧室形成的混气较为均匀, 其燃油分布在很大程度上由气流控制, 不受燃油流量限制, 因此其出口温度分布均匀。图 6反映出燃烧室良好的出口温度场均匀度, 温度系数低于 9%, 说明燃烧室内气流组织合理、燃烧均匀、火焰较短。

4 结 论

（1）对于高温升燃烧室的设计, 采用燃油具有自身预热、蒸发并与空气预混效果的蒸发型结构方案是一种适宜的选择;

（2）燃烧室的流量分配及火焰筒的开孔规律是合理的;

（3）一定的性能实验结果说明, 燃烧室的性能参数能够满足热风洞的工作要求;

（4）从实验后的分解情况看, 火焰筒和蒸发管完好, 无过热和烧蚀现象, 说明燃烧室的安全措施和冷却结构是可靠的;

（5）实验过程表明, 所设计的燃烧室不适合在出口温度低于 1 173 K的状态下工作, 因为过于低温状态下工作, 由于供油量较小, 蒸发管出口的余气系数增大很多, 蒸发管内易产生回火现象, 导致燃烧过程出现脉动, 严重时会危及蒸发管的安全。

蒸发型燃烧室由于结构简单、紧凑, 空间利用合理, 可有效扩大燃油的预热面积, 改善火焰筒内的燃烧过程, 因而性能参数较高, 具有较好的适用范围和工程实用价值。本设计技术和方法可为今后此类高温升燃烧室的研制提供借鉴和参考。

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tion that our country currently has not yet made available necessary conditions for producing any light type gas turbines, such type of turbines should not be chosen as far as possible. Each station shall be provided with at least three gas turbines and can be built in phases or stages with space being reserved for the extension project. This not only relates to the safe and smooth operation of the long-distance transmission pipeline but also has an extremely big influence on its operation cost. On the basis of an analysis of theoretical and actual operation effectiveness, the authors have studied and explored in depth the foregoing two major technical problems. Key words: long-distance transmission pipeline, gas turbine/compressor unit, machine type, configuration

变几何燃气轮机性能的计算分析＝Calculation and Analysis of the Performance of a Variable Geometry Gas Turbine[刊，汉] / QIU Chao, SONG Hua-fen (College of Mechanical and Power Engineering, Shanghai Jiaotong University, Shanghai, China, Post Code: 200240) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(4). —377～380

To analyze the performance of a unit when its turbine is being geometrically changed, proposed was a new method for studying the performance of variable geometry gas turbines based on a small deviation equation. By using the method, the unit performance was calculated when the relative change of different turbine flow path areas is within ±5% and a theoretical analysis has been performed. The analytic results show that in simple cycle units, whether a HP turbine, LP turbine or geometrically changed power turbine is used, it will have little influence on the cost-effectiveness of the system but will affect the equilibrium operating lines of the compressor. Among others, the variable geometry of the LP turbine will have a relatively big influence on the equilibrium operating lines of the LP compressor while that of both HP and LP turbine will also exercise a relatively big effect on the same operating lines of the HP compressor. Key words: small deviation equation, variable geometry gas turbine, performance study

燃气轮机控制室中央空调自控系统的设计与应用＝Design and Application of a Central Air-conditioning Automatic Control System in a Gas Turbine Control Room[刊，汉] / WANG Qi-xiang, XIE Xian-gang, SONG Chun-hua, et al (School of Maritime Affairs and Harbor Navigation, Guangdong Traffic Vocational Technical College, Guangzhou, China, Post Code: 510800) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(4). —381～384

Designed was a configuration-software-based automatic control system for the central air conditioning in a gas turbine control room. With PLC (programmable logic controllers) and configuration software serving as a core, the system employed distributed remote modules to accomplish data acquisition and transmission of control signals. The operation results show that depending on the correlation among the transducers, transmitters, PLC and actuators in the automatic control system, the authors have employed a man-machine-friendly interface to set and reflect the control parameters of the system, facilitating the setting, operation and management of relevant parameters, thus optimizing the distributed control system of central air conditioners. Key words: gas turbine control room, PLC (programmable logic controllers), central air conditioning, automatic control, configuration software

高温升蒸发型燃烧室的设计＝Design of a High-temperature-rise Evaporation Type Combustor[刊，汉] / LI Ming, WU Er-ping, TANG Ming (College of Power and Energy Source, Northwest Polytechnic University, Xi'an, China, Post Code: 710072) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(4). —385～388

To meet the requirement of a combustor in a ground surface test facility for a high temperature rise, designed was an evaporation type combustor with a temperature rise of 1 350 K. According to the overall structure of the combustor, its main components were designed. Through the aerodynamic and thermodynamic calculation of the combustor, the

overall dimensions of the combustor and the opening hole dimensions of the flame tube were determined. On this basis, a performance test of the combustor was conducted to a certain extent. The test and application results show that the combustor thus designed features a safe and reliable operation, a simple structure, as well as a high space utilization rate, a quick temperature rise speed and a clean exhaust gas. In the whole operation range, the combustion efficiency can reach 0.95 ~ 0.97 and the non-uniformity of the temperature field at the outlet is lower than 0.09, thus meeting the design requirements. Key words: gas turbine, high temperature rise, evaporation type, combustor

余热电站热力系统建模及蒸汽参数优化 = Modeling and Steam Parameter Optimization for the Thermodynamic System of a Waste Heat Power Plant[刊,汉] / ZHAO Bin, XU Hong, ZHANG Cai-juan (Education Ministry Key Laboratory on Power Plant Equipment Condition Monitoring and Control, North China University of Electric Power, Beijing, China, Post Code: 102206), LIU Xiao-wen (Hebei Provincial Key Laboratory on Modern Metallurgical Technologies, Hebei University of Science and Technology, Tangshan, China, Post Code: 063009) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(4). —389 ~ 393

The choice of a thermodynamic system and its steam parameters is the most important basic work for designing a waste heat power plant. With the dual pressure system in a sintering waste heat power plant in Jinan Iron and Steel Works serving as an example, established was a model for calculating a thermodynamic system and optimizing its steam pressures with a maximum net power output serving as the target function. In addition, a program was designed and the correctness of the model was verified through calculations. The main factors influencing the optimization of the main steam pressure were analyzed, and the law governing the change of net power output with the main steam pressure was studied. The research results show that the optimum main steam pressure of a case calculation is 2.2 MPa, 0.14 MPa higher than the main steam design pressure of the power plant. The research findings can offer a relatively scientific basis for the optimized design and operation of low pressure waste heat power plants. Key words: waste heat power plant, thermodynamic system, mathematical model, program computation, main steam pressure optimization

Ω型惯性气液分离器性能研究 = Performance Study of a Ω Type Inertia Gas-liquid Separator[刊,汉] / LUAN Yi-gang, SUN Hai-ou, WANG Song, et al (College of Power and Energy Source Engineering, Harbin Engineering University, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(4). —394 ~ 398

With the help of a numerical simulation method, predicted was the status of the flow field inside a Ω type gas-liquid separator. In the calculation, the two-dimensional Reynolds time-averaged N—S equation was adopted, and the standard model has been used as the turbulent flow model to obtain and understand the distribution characteristics of the flow field inside the separator. Moreover, the performance of the separator with different clearances was studied and a model was fabricated to conduct a test in a wind tunnel. The theoretical calculation results were verified, and the resistance and efficiency characteristics of the separator obtained. It has been found that the separator has a relatively high gas-liquid separation efficiency and the blade spacing exercises a very big influence on the separation efficiency. When the Ω type blade spacing is 18.2 mm, the average separation efficiency can reach over 90%. Key words: Ω type gas-liquid separator, numerical simulation, model test, drag force, separation efficiency

造气炉渣与无烟煤混合燃料燃烧特性分析 = Analysis of Combustion Characteristics of a Gas Production Slag and Anthracite Mixed Fuel[刊,汉] / GAO Yu-fen, WANG Peng, LI Hong-jun (Engineering Project Installation Team, Department of Combined Service Forces, Shenyang Military Region, Liaoyuan, China, Post Code: